Multibeam Observations of Mine Burial Near Clearwater, FL, Including Comparisons to Predictions of Wave-Induced Burial

Monica L. Wolfson, David F. Naar, Peter A. Howd, Stanley D. Locker, Brian T. Donahue, Carl T. Friedrichs, Arthur C. Trembanis, Michael D. Richardson, and Thomas F. Wever

***Abstract*—A Kongsberg Simrad EM 3000 multibeam sonar (Kongsberg Simrad, Kongsberg, Norway) was used to conduct a set of six repeat high-resolution bathymetric surveys west of Indian Rocks Beach (IRB), just to the south of Clearwater, FL, between January and March 2003, to observe *in situ* scour and burial of instrumented inert mines and mine-like cylinders. Three closely located study sites were chosen: two fine-sand sites, a shallow one located in ~13 m of water depth and a deep site located in ~14 m of water depth; and a coarse-sand site in ~13 m. Results from these surveys indicate that mines deployed in fine sand are nearly buried within two months of deployment (i.e., they sunk 74.5% or more below the ambient seafloor depth). Mines deployed in coarse sand showed a lesser amount of scour, burying until they present roughly the same hydrodynamic roughness as the surrounding rippled bedforms. These data were also used to test the validity of the Virginia Institute of Marine Science (VIMS, Gloucester Point, VA) 2-D burial model. The model worked well in areas of fine sand, sufficiently predicting burial over the course of the experiment. In the area of coarse sand, the model greatly overpredicted the amount of burial. This is believed to be due to the presence of rippled bedforms around the mines, which affect local bottom morphodynamics and are not accounted for in the model, an issue currently being addressed by the modelers. This paper focuses specifically on two instrumented mines: an acoustic mine located in fine sand and an optical instrumented mine located in coarse sand.**

***Index Terms*—Mine burial, multibeam bathymetry, scour modeling.**

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I. Introduction

The ability to detect buried mines on the seafloor remains one of the most difficult tasks in mine countermeasures. Morphodynamics of the seafloor are often responsible for the burial of heavy objects, including, but not limited to, pipelines, breakwaters, concrete, debris, and mines [1]. In such cases, burial is defined as the percent subsidence of the object below the ambient seafloor. Mines are readily buried on impact and by secondary processes such as scour and fill, liquefaction, and changes in seafloor morphology. While mine-hunting techniques successfully locate mines resting on the seafloor, a partially buried mine can avoid sonar detection and requires either mine sweeping or complete area avoidance [2]. It is, therefore, useful to develop methods of predicting mine burial under different environmental conditions and varying temporal scales. The ability to predict how quickly scour will form around a mine and how quickly the mine will become buried under different energy and geological conditions is important in designing search strategies.

Mine burial experiments sponsored by the U.S. Office of Naval Research (ONR, Arlington, VA) were conducted approximately 20 km off the coast of Indian Rocks Beach (IRB), near Clearwater, west-central Florida, between January 8 and March 12, 2003. Repeat high-resolution multibeam bathymetry data were collected using a Kongsberg Simrad EM 3000 (Kongsberg Simrad, Kongsberg, Norway) and used to provide *in situ* observations of mine scour and burial throughout the experiment. These data were also used to test a 2-D wave-induced scour model. Herein, the term mine actually refers to inert mine-like cylinders. For the purposes of this paper, percent mine burial was defined as percent of mine subsidence with respect to the ambient seafloor, given by

$$\%\text{burial} = \left(\frac{D_m - (d_s - d_m)}{D_m}\right) \times 100 \quad (1)$$

where D_m is the diameter of the mine, d_m is depth of the mine (measured as the shallowest point on the mine surface), and d_s is the depth of the ambient seabed (approximated from the multibeam images). An identical equation was used by Trembanis *et al.* [3], which allowed for a direct comparison between the multibeam observations and the model predictions.

II. Environmental Conditions

A. Geologic Setting

The IRB study area was selected using sidescan, seismic, and multibeam data, as well as sediment cores, to determine thick-

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14. ABSTRACT

***Abstract*—A Kongsberg Simrad EM 3000 multibeam sonar (Kongsberg Simrad, Kongsberg, Norway) was used to conduct a set of six repeat high-resolution bathymetric surveys west of Indian Rocks Beach (IRB), just to the south of Clearwater, FL, between January and March 2003, to observe *in situ* scour and burial of instrumented inert mines and mine-like cylinders. Three closely located study sites were chosen: two fine-sand sites, a shallow one located in ~13 m of water depth and a deep site located in ~14 m of water depth; and a coarse-sand site in ~13 m. Results from these surveys indicate that mines deployed in fine**

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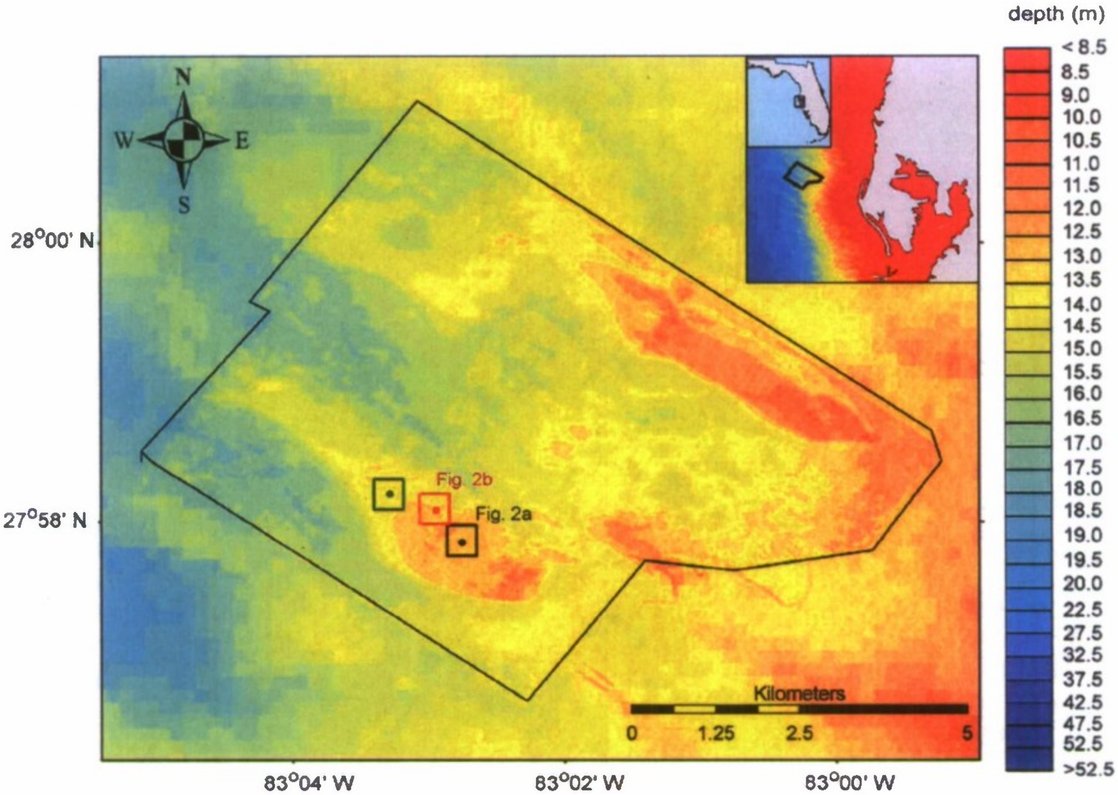

Fig. 1. Location of the experiment site off IRB. The area outlined with a thin black line represents the data obtained in April 2002 during the site survey. The black and red symbols indicate the location of the primary fine- and coarse-sand sites, respectively, and are shown in detail in Fig. 3. The green symbol represents the location of the deep fine-sand site. Additional digital data was provided by the U.S. Geological Survey (USGS, St. Petersburg, FL; see [14]) and the National Oceanic and Atmospheric Administration (NOAA, Washington, DC; courtesy of D. Scharff, 2004). Figure was modified from [15].

ness of sediments, flatness of seabed, and location of fine versus coarse sands. This area is dominated by northwest–southeast trending siliciclastic shoreline-oblique sand ridges separated by patches of coarse-grained carbonates and exposed hard bottom (karsified limestone; Fig. 1). The siliciclastic sand ridges are predominantly composed of fine-grained quartz sands (median grain size 0.180 mm) while the coarse-grained carbonates are composed mainly of reworked shell hash (median grain size 0.840 mm) [4]. Three sites were selected within the study area to provide a comparison of mine scour and burial under these varying geologic regimes.

Site 1, located on one of the dominant sand ridges, served as the primary deployment location and was composed of fine sands approximately 13 m below mean lower low water (MLLW). Site 2 was situated approximately 200 m northwest of site 1 within a rippled scour depression (RSD) cutting south–southwest through the sand ridge (Fig. 2). The RSD was composed of the same reworked shell hash separating the sand ridges within the study area; average depth within the RSD was approximately 13 m. Site 3 was secondary fine-sand site located roughly 600 m from site 1 in approximately 14 m of water depth.

B. Oceanographic Conditions

The IRB study area is a wave-dominated environment with most waves arriving from the west–southwest. Waveheights are typically larger during early fall to winter months when larger storm events are more prevalent in the Gulf of Mexico. Significant waveheight over the course of the IRB experiment averaged between 0.5 and 1 m. Wave events with significant waveheights over 1 m occurred nine times, with three of these events having significant waveheights greater than 2 m (Julian days 17, 24, and 54). Bottom currents are tidally dominated, with prevailing flow to the north–northwest and south–southeast.

III. Methodology

A. Equipment

1) Acoustic Mines: The U.S. Naval Research Laboratory (NRL, Stennis Space Center, MS) in conjunction with Omni Technologies, Inc. (New Orleans, LA) designed four acoustically instrumented mines (AIMs) for use in the ONR mine burial experiments. Each AIM has 112 acoustic sensors mounted flush with the surface capable of measuring surface burial at each location. These transducers are also capable of measuring the changing dimensions of the scour pit over time. The AIMs are also equipped with three-axes accelerometers and three-axes compasses to measure roll, pitch, and heading. Six pressure sensors monitor changes in mean water depth. The mines are encased in a naval marine bronze due to its antifouling, nonmagnetic, high-density properties. Each AIM is cylindrically shaped with a length and diameter of 2.03 and 0.53 m, respectively, and a weight of 800 kg fully loaded (Fig. 2) [5]. Four AIMs were deployed during the IRB experiment, all located with the primary fine-sand site [Fig. 3(a)].

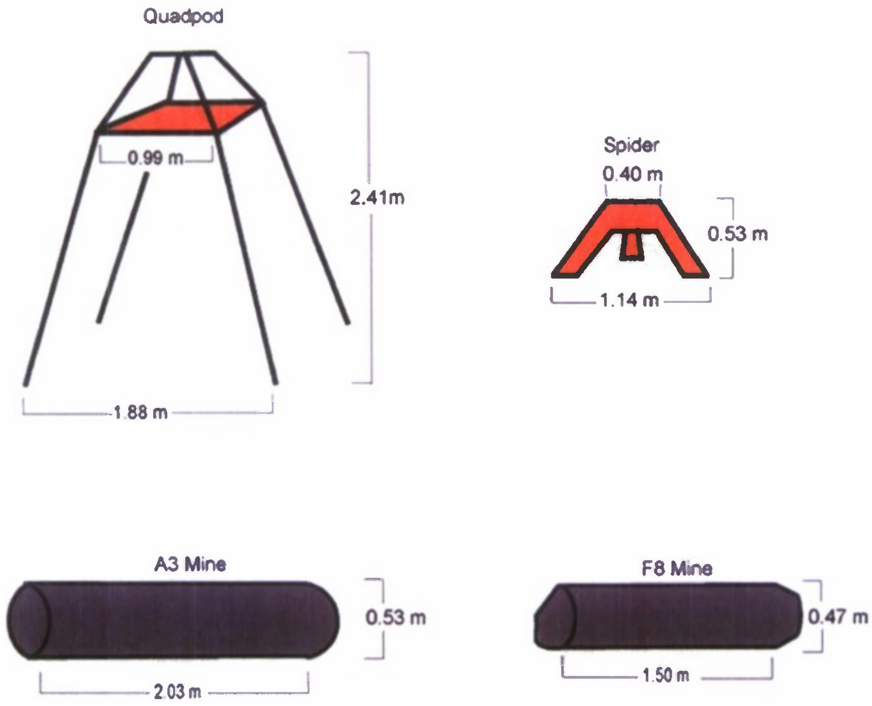

Fig. 2. Dimensions of the quadpods, spiders, and acoustic mine-like cylinders visible in the multibeam images.

2) Optical Mines: Forschungsanstalt der Bundeswehr für Wasserschall-und Geophysik (FWG, Kiel, Germany) developed an optically instrumented mine that was also used in the ONR mine burial experiments. The FWG mines have three rings of paired optical sensors mounted at 15° intervals around the mine that measure burial. Light-emitting diodes (LEDs) transmit an optical signal that is received by a phototransistor. If the signal is blocked then the sensor is assumed buried; percent burial equals the percentage of blocked sensors. Roll and pitch of the FWGs are measured via a three-axes accelerometer; however, the steel casing of the mine does not allow for measurements of heading due to its high potential of magnetism. Each FWG is 1.5 m long and 0.47 m in diameter, with a fully loaded weight of 619 kg (Fig. 2). Six FWGs were deployed during the IRB experiment, two in the primary fine-sand site, two in coarse-sand site [Fig. 3(b)], and two in the secondary fine-sand site.

3) Quadpods and Spiders: To monitor current and wave interactions with the mines and the seafloor, and their subsequent effect, three instrumented quadpods and five tripods (spiders) were deployed near the mines. Each quadpod was fitted with a 1.5-MHz pulse coherent boundary layer profiler [SonTek pulse coherent acoustic Doppler profiler (PC-ADP), SonTek, San Diego, CA], a 5-MHz acoustic Doppler point current meter (SonTek Hydra), an *in situ* grain-size sensor [laser *in situ* scattering and transmissometry (LISST-100)], a conductivity/temperature sensor (SeaBird Microcat C-T, SeaBird Electronics, Inc., Bellevue, WA), and an optical backscatter sensor [Downing optical backscatter sensor (OBS)]. Each spider was equipped with a 1.5-MHz bottom mounted ADP with wave directional capabilities (SonTek ADP). Two quadpods and one spider were deployed in the primary fine-sand site, and one quadpod and one spider were deployed in the coarse-sand site.

4) Multibeam Sonar: The use of multibeam sonars as tools for both bathymetric mapping and backscatter imaging is well established ([6]–[10] and references therein). For the IRB mine burial experiment, a Kongsberg Simrad EM 3000 sonar was used. The EM 3000 is a 300-kHz multibeam swath sonar with 127 overlapping 1.5°× 1.5° beams, producing a 130° swath transverse to ship heading. Kongsberg Simrad lists the EM 3000's vertical uncertainty as 5–10 cm [root-mean-square (rms) error] depending on depth. The average depth of the IRB study site is ~13 m, which falls into the shallow-water range.

During the surveys, the sonar was pole-mounted to the ship allowing for precise positioning when used in conjunction with the TSS (now Applanix, Richmond Hill, ON, Canada) positioning and orientation system for marine vessels (POS/MV) 320 system. The POS/MV is composed of an inertial motion unit (IMU) with global positioning system (GPS) azimuth measurement system (GAMS) integrated with real-time kinetics (RTK). The Clearwater Beach Adams Mark Hotel was used as a base station during the IRB experiment for all RTK measurements. This combined system provides positioning accuracy on the order of ±10 cm, and roll, pitch, and yaw measurements accurate to 0.02°. The positioning accuracy is extended to ±1 m based on other installation parameters and water-column properties. The POS/MV system with RTK capabilities also provides real-time heave correction with a measurement accuracy of 5 cm or 5% of the heave amplitude (whichever is greater) for periods up to 20 s. Sound speed profiles were collected at the start of each survey using a SeaBird Electronics Inc., Bellevue, WA, conductivity–temper-

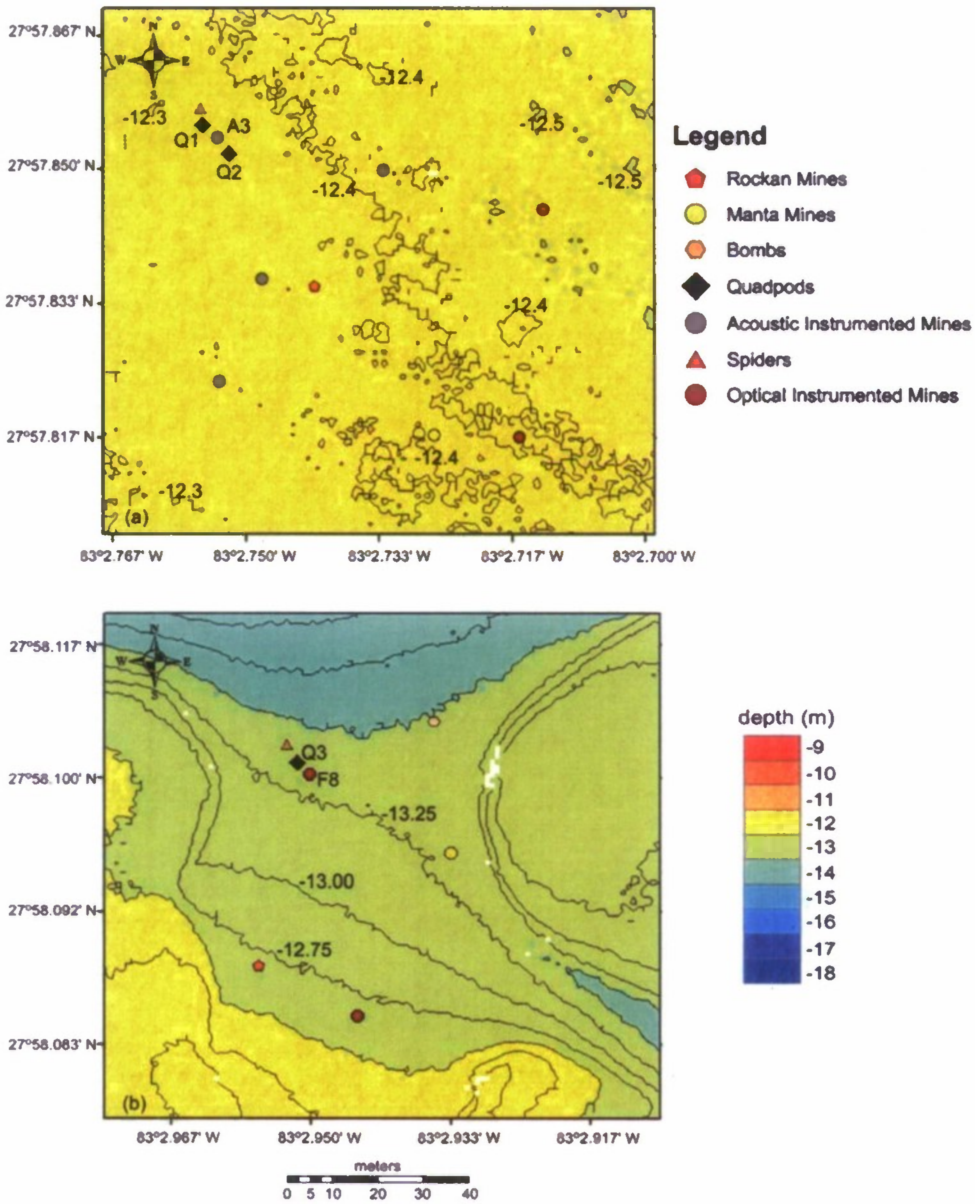

Fig. 3. Location of the deployed equipment for the primary (top) fine- and (bottom) coarse-sand study sites. The contour interval for images (a) and (b) are 0.10 and 0.25 m, respectively.

ature–depth sensor (CTD SBE 19). Total error propagation for the entire system was 7 cm when GAMS was online and 11 cm when it was not. All multibeam data were collected during six cruises throughout the 2003 experiment: January 8–11, when the mines were deployed; January 12–13 and 16–17, when the quadpods and spiders were deployed; and January 19–20, February 5–6, and March 12–13, when all deployed equipment was retrieved.

B. Data Processing

1) Tide Analysis: Before any gridding and analysis, all multibeam data for the IRB experiment were tide-corrected to mean lower low water (MLLW) using a local tide record obtained from the SonTek PC-ADP deployed on the quadpods during the experiment. While tide-correction is nothing new to multibeam data processing, the methods used to provide the local tide records for this experiment also provided a new means for distinguishing between apparent changes in water level due to the pressure sensor mount (in this case a quadpod) settling into the seabed and changes due to actual localized seabed elevation and to sediment transport. Vertical shifts of the pressure sensor due to sinking of the quadpod into the sediments were corrected by verifying that the pressure sensor depth plus height of the sensor above the seabed remained constant (Fig. 4). The tide record was obtained by calibration of the pressure sensor record by the NOAA Clearwater Station 8726724 (Fig. 5). Application of this analysis to the multibeam data effectively removed any changes of sea level related to tides and sea level setup caused by winds. Multibeam data from surveys before the quadpods deployed on January 16 were tide-corrected with NOAA station

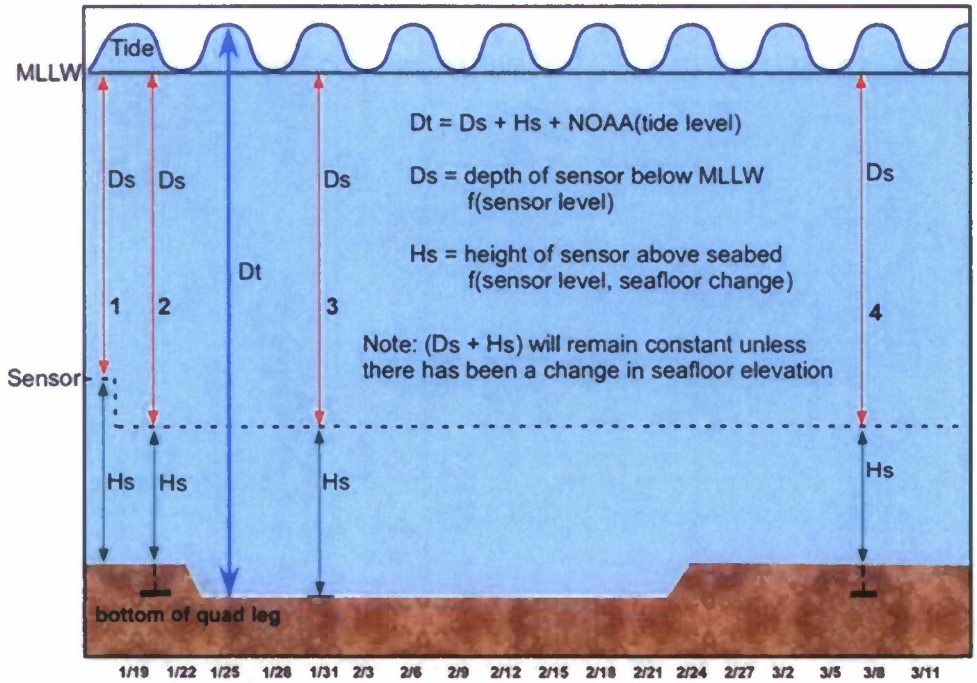

Fig. 4. Cartoon schematic indicating the difference between apparent water level changes due to pressure sensor settling and actual changes in seabed elevation. In the first instance, between cases 1 and 2, the sensor settles into the seabed. In the second instance, between cases 2 and 3, and the third instance, between cases 3 and 4, seabed elevation changes occur due to sediment transport.

sea level data. A multiplier of 0.94 was applied to the NOAA tide record to account for the difference in amplitude between the NOAA tide and the tide records obtained from the pressure sensors during this initial period. For a full description of the methods used to extract the tide records used in this experiment, refer to [11].

2) Multibeam Data Processing: All multibeam data were cleaned and processed using CARIS (Fredericton, NB, Canada) HIPS and SIPS 5.3 software. All speed jumps greater than 1 kn and all time jumps greater than 1 s between consecutive pings were removed using a linear interpolation. Once the data were cleaned and the tide correction was applied, the multibeam data were gridded in CARIS using a weighted-mean gridding algorithm. The weight that any given sounding contributes to the grid varies with range and grazing angle to the seabed. The range weight is inversely proportional to the distance from the grid node (i.e., the closer to the node, the greater the weight). The grazing angle weight is most important in grids containing adjacent or overlapping track lines. Higher weight is given to beams from the inner part of the swath. Beams with a grazing angle between 75°–90° are given a weight of 1.0. This weight linearly decreases to 0.01 as the grazing angle with the seabed decreases to 15°.

For each survey, 18 × 18-m grids centered on the mines were created, gridded at a 20-cm horizontal resolution and referenced to MLLW. The EM 3000 multibeam has a beamwidth of 1.5° at nadir, giving it an effective footprint of ~28 cm in 13 m of water depth (the sonar is mounted ~2 m below the water surface). The across-track beam spacing is 0.9° at nadir, giving an overlap of 0.6°, which equates to ~11 cm in ~13 m of water depth. Therefore, a horizontal gridding resolution of 20 cm was deemed reasonable for this paper.

In some instances, the 20-cm grid resolution was too small to provide full coverage in areas of sparse data (e.g., the outer beam of the swath). In these cases, the grids were interpolated to fill these data gaps. Interpolation was based on a 3 × 3-grid node area with a threshold level of six neighbors. For example, if a node in the grid does not contain a value, the interpolation is limited to the neighboring nine nodes. In order for the interpolation to take place, a minimum of six of these neighboring nodes must contain a pixel value. This helps limit the amount of interpolation and prevents it from expanding the gridded surface outward from the actual survey area. Final imaging, including 3-D rendering and artificial sun illumination, was completed using interactive visualization software (IVS_ Fledermaus 6.0).

To analyze scour formation, bathymetric finite difference grids were created by subtracting the bathymetric grid from the first survey over the mine from the bathymetric grid from the final survey. This resulted in a difference grid showing areas of deposition (positive values) and erosion (negative values) between the two surveys. These grids have a vertical accuracy of ±10 cm due to the combined ±5-cm vertical accuracy of the multibeam surveys. Although difficult to estimate, the surface area accuracy is assumed to be ±2 m based on the combined 1-m positional accuracy of the multibeam; however, the number may be overly conservative. The scour pit was then contoured in 10-cm intervals and the area within each contour was calculated. The first contour of the scour was defined as the shallowest contour that formed a closed polygon around the pit. Two cross sections were taken across each scour pit, a long profile passing through the deepest points of the pit and a short profile cutting through the shallowest points. All scour analysis was completed using ArcGIS 9.

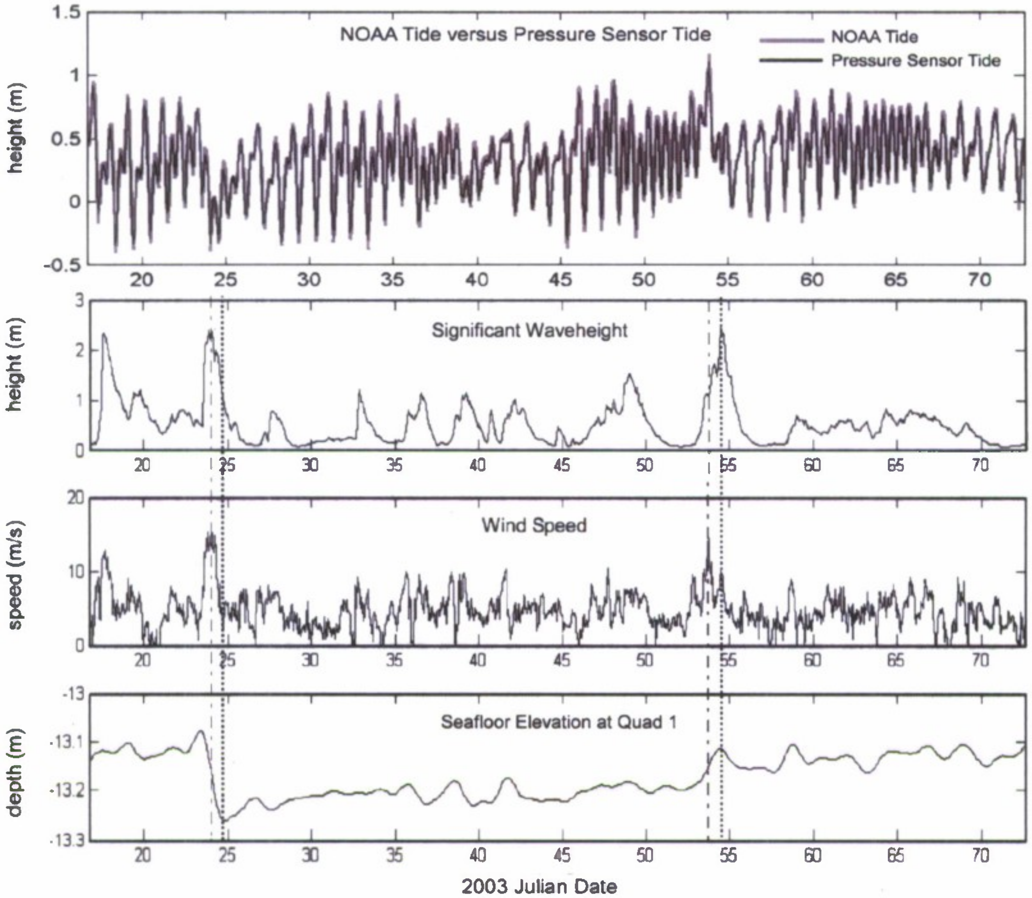

Fig. 5. Top graph shows the NOAA tide versus the tide extrapolated from the pressure sensor data. The second graph shows significant waveheight obtained from the acoustic Doppler current profiler (ADCP), and the third shows wind speed in meters per second obtained from the NOAA buoy. The bottom graph shows calculated seafloor depth underneath quadpod 1 based off the pressure sensor data and the isolated tide record. Note that the greatest rates of change in seafloor elevation match up with peak wind speed and peak significant waveheight.

IV. Results

A. Multibeam Observations

1) A3 Mine: The A3 mine was deployed at ~11:00:00Z on January 8, 2003 within the primary fine-sand site at a water depth of 12.81 m. The self-contained underwater breathing apparatus (SCUBA) divers repositioned the mine in a north–south orientation at 21:00:00Z on January 8, 2003, ensuring an initial burial of zero percent. The first multibeam survey over the mine occurred 49 h (Jan. 10) after reposition. Only the A3 mine was visible at the time of this survey, as the quadpods and spider were not deployed until January 16 [Fig. 6(a)]. The depth to the top of the mine was 12.32 m, with an average ambient seafloor depth around the mine of 12.81 m. The difference, 0.49 m, indicates that the mine was approximately 7.5% buried after two days. There was no evidence of scour around the mine during this survey. The EM 3000 multibeam sonar offers a target detection beam mode which widens the beams from 1.5° to 4.0°, to increase bottom target detection capabilities. Target detection was enabled at the time of this survey, as well as the following survey from January 13, as it was not discovered until data processing that this beam mode blurs the mine surface and can cause a distortion in the apparent mine orientation. As a result, the mine appears to be oriented more northeast–southwest in the multibeam image, rather than the actual north–south orientation recorded by the compass within the mine and validated by SCUBA diver observations.

At 103 h past reposition (January 13), the depth of the mine has increased to 12.42 m, indicating a sinking of 0.10 m in 54 h [Fig. 6(b)]. The average depth of the seafloor around the mine was 12.88 m, resulting in a burial of 13.2% in five days. Again, no scour was yet evident surrounding the mine and the target detection mode caused a distortion of mine orientation. The third survey over the mine occurred 197 h postreposition (January 17), one day after the deployment of the spiders and quadpods. The mine, quadpod 2, and the spider are all clearly visible, yet quadpod 1 does not show up [Fig. 6(c)]. At the time of the survey, a medium spike filter was applied to the raw multibeam data to decrease the number of erroneous data pings. If a depth measurement for a particular ping falls too far below or above that of surrounding pings, the ping is considered erroneous and is deleted. The legs of the quadpod are small in diameter and curve up over the top of the equipment platform, resulting in a small surface area for the quadpod overall. It is, therefore, possible that only a few pings hit off the quadpod as the sonar passed

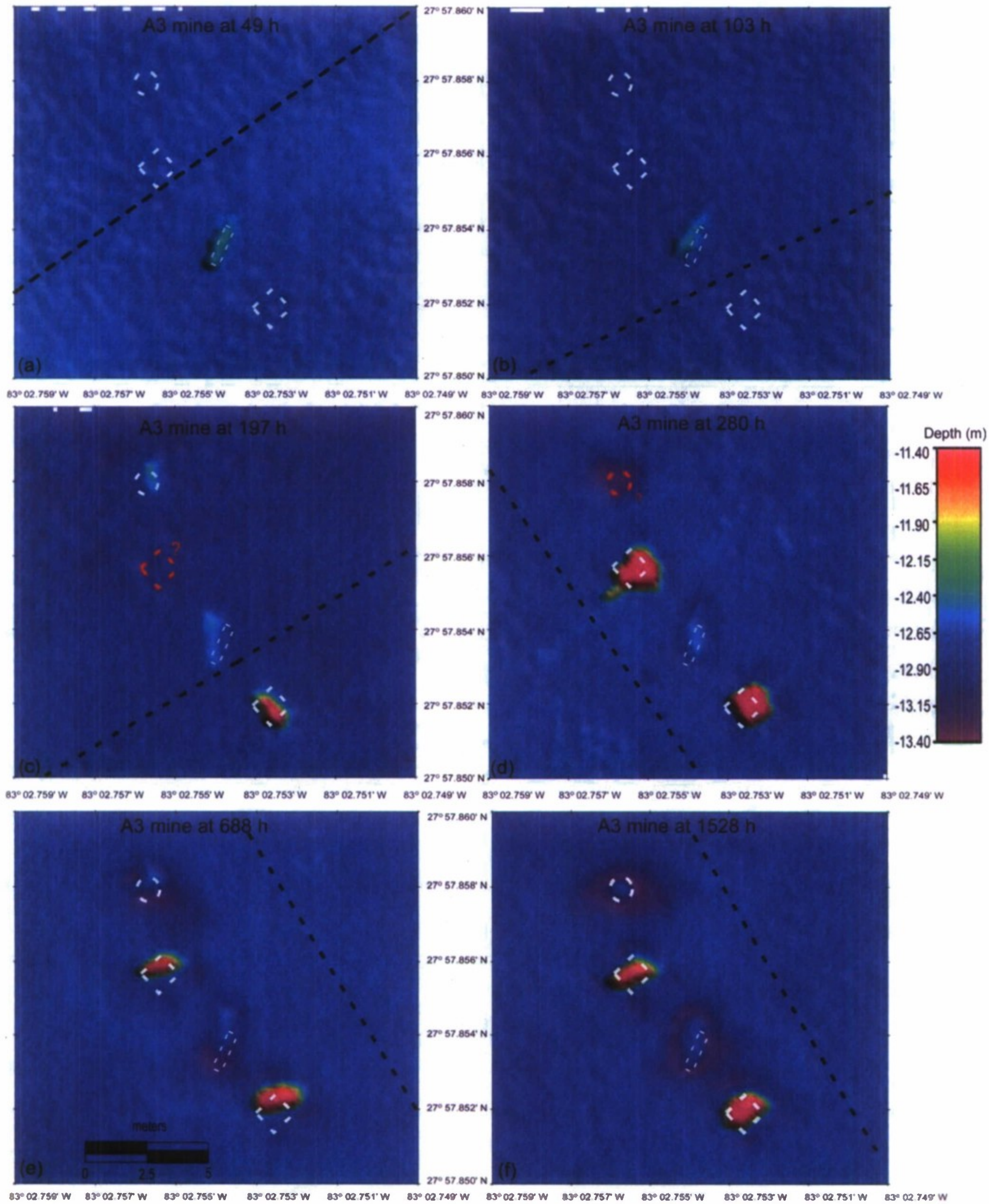

Fig. 6. Multibeam imagery of the A3 mine over the course of the experiment. The black dashed lines represents the ship track during the survey. White outlines are scaled to the actual dimensions of the deployed equipment. The mine outline remains at the same scale and orientation as it does in the first image throughout the rest of the images as a reference.

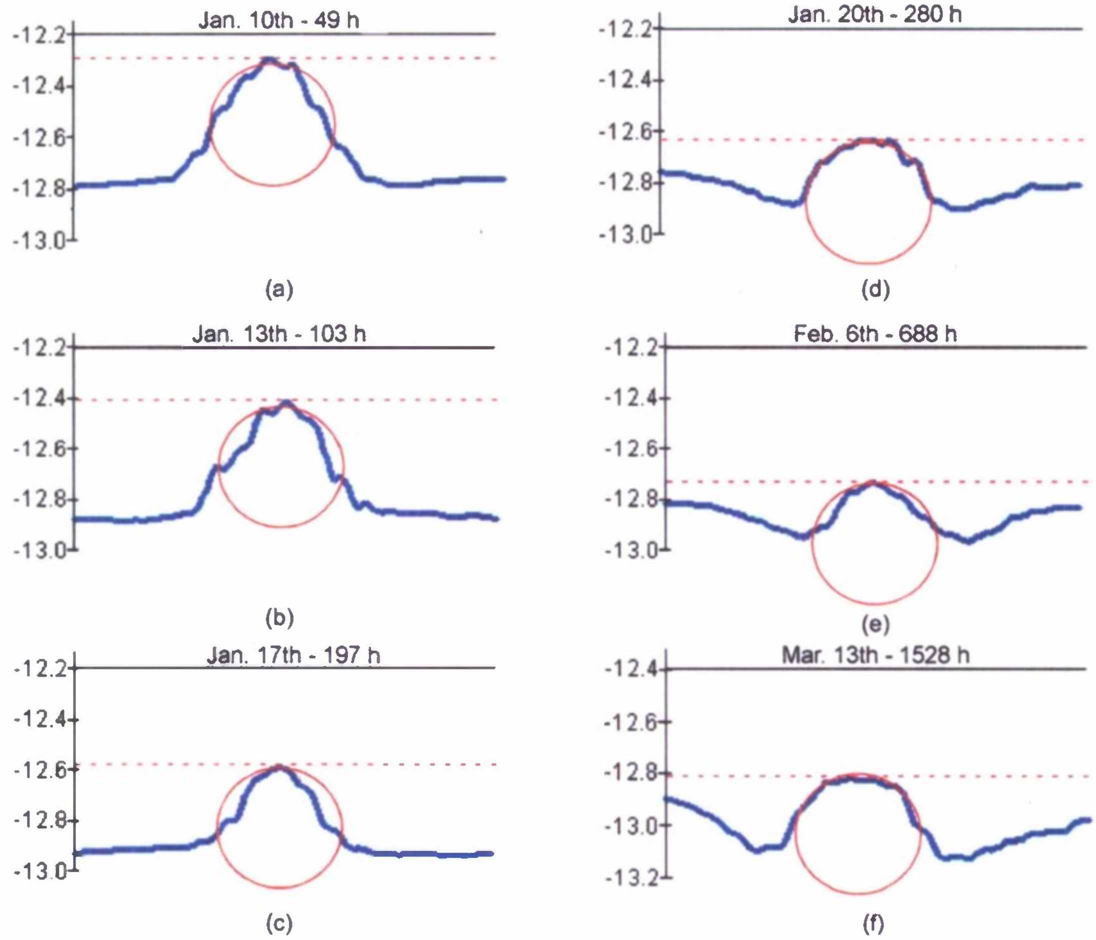

Fig. 7. Progression of mine burial for the A3 mine over the course of the experiment. Profiles were taken at the center point of the mine along the short axis. The red dashed line indicates the depth of the center point of the mine. This depth does not necessarily coincide with the shallowest point on the mine surface used for calculating the percent of mine burial. The red circle represents the true diameter of the mine (0.53 m). Scour can clearly been seen developing at the sides of the mine in (d)–(f).

overhead, resulting in the pings being determined erroneous by the spike filter.

Although there was no scour evident around the mine during this survey, the depth of the ambient seafloor was 12.92 m, indicating a localized erosion of 11 cm since the first survey seven days before. The depth to the top of the mine was 12.48 m, signifying the mine had sunk 0.16 m for a total burial of 17.0%. Target detection mode had been turned off during this and all subsequent surveys, allowing for sharper imaging of the mine and a more accurate depiction of orientation.

In the January 20 survey, 280 h after the mine was repositioned, the mine appeared to be 62.3% buried [Fig. 6(d)]. The depth to the top of the mine was 12.62 m, 0.14 m deeper than that observed during the previous survey. The average depth of the seafloor around the mine was 12.82 m, an increase of 10 cm in just three days. A storm event passing through the area on January 17 resulted in increased wave energy, which in turn increased the rate of wave-induced scour and might have also caused a pileup of sand around the mine. The spider was not visible in the data, believed to also be the result of the spike filter used during data collection. Scour around the mine was evident

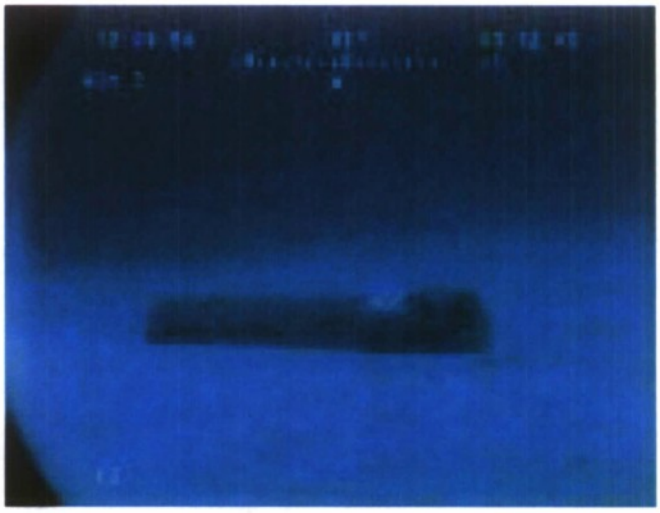

Fig. 8. ROV video still of the A3 mine taken on March 12, 2003, one day before the final multibeam survey. The camera is facing east–northeast looking down into the scour pit. An exact scale cannot be provided since the camera is facing the mine at an angle; however, the mine is approximately 2.03 m long.

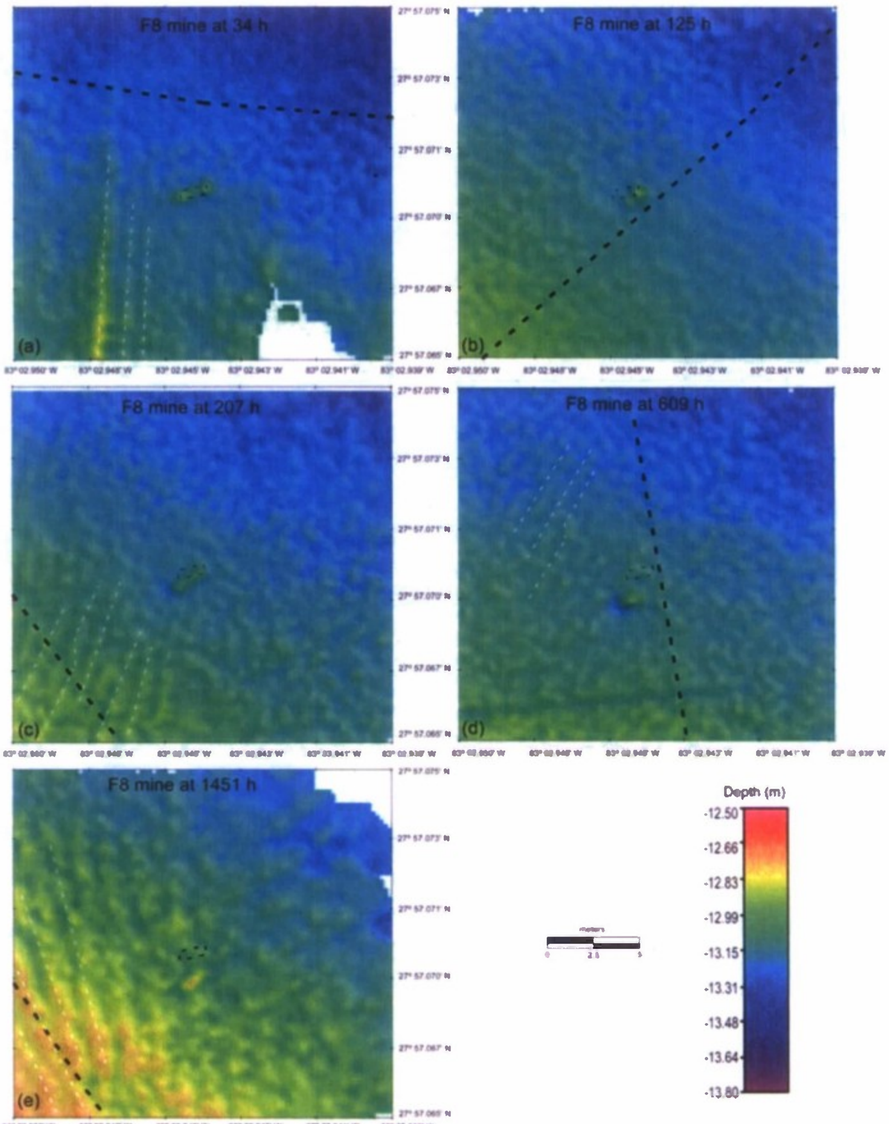

Fig. 9. Multibeam imagery of the F8 mine over the course of the experiment. The black dashed lines represent the ship track during the survey. Black outlines are scaled to the actual dimensions of the deployed equipment. White dashed lines are used to point out ripples in the images. The mine outline remains at the same scale and orientation as it does in the first image throughout the rest of the images as a reference.

during this survey, with a maximum depth within the scour pit of 13.04 m.

On February 6, 688 h into the experiment, the A3 mine was 83.0% buried [Fig. 6(e)]. The depth of mine was measured at 12.72 m, indicating that, in the 28 days the mine had been in the environment, it had sunk 40 cm. The average depth of the seafloor around the mine remained relatively unchanged since the previous survey, measured at 12.81 m. The scour pit had further developed around the mine and maximum depth within the pit increased to 13.18 m.

The final survey over the A3 mine occurred on March 13, 1528 h after the mine was repositioned by divers. The mine itself was not apparent in data and was only detectable due to the defining ring of scour that had developed around its periphery [Fig. 6(f)]. The depth of the mine was measured at 12.80 m, indicating the mine had sunk a total of 0.48 m since the start of observations (Fig. 7). The average depth of the seafloor around the mine was 12.82 m, resulting in an observed burial of 96.2%. The spider had also scoured considerably and sunk into the seafloor. Scour also became evident around the legs of both quadpods, though any sinking of the quadpods appeared to be minimal, according to pressure sensor data on the quadpod and multibeam bathymetry data. SCUBA diver observations and remotely operated vehicle (ROV) video showed that the A3 mine was resting within an extended scour pit at the end of the experiment, and corroborated the multibeam data (Fig. 8).

2) F8 Mine: The F8 mine was located at site 2, situated within an RSD over coarse sand at a water depth of 13.20 m. The mine was deployed at 23:00:00Z on January 11, 2003; unlike mine A3, divers did not need to reposition the mine. The January 13 survey was first to image the F8 mine, 34 h after its deployment [Fig. 9(a)]. The mine had only been in the environment for approximately two days and no scour was evident around the mine. The depth to the top of the mine was 12.72 m, with

an average ambient seafloor depth around the mine of 13.20 m. The difference of 0.48 m between the top of the mine and the seafloor is actually 1 cm greater than the diameter of the mine itself (0.47 m) but can be accounted for by the 5-cm vertical uncertainty of the multibeam sonar. It is also important to keep in mind that the ambient seafloor depth was an approximate regional estimate, based on an average of 35 measurements taken around the mine. A north–south trending ripple field was observed during the survey and can be seen in the lower left corner of the image. Diver observations provided independent verification of the presence of these ripples. Maximum height of the ripples was $\sim$20 cm with a maximum wavelength of $\sim$1.25 m. There was no observed burial of the mine at this time.

Increased waveheights from a storm event passing over the area during the time of the January 17 survey appear to have modified the ripples into a more mottled appearance, which may represent disorganized beds of varying magnitude [Fig. 9(b)]. Bedforms of this nature were observed in this area during ROV and SCUBA diver operations at different times throughout the experiment. The depth of the mine was 12.80 m, indicating the mine had sunk 8 cm in the 125 h since its deployment. The average depth of the seafloor around the mine was 13.17 m, resulting in an observed burial of 21.3%. There was no scour evident around the mine at the time of this survey. At 207 h (January 20) into the experiment, scour had become visible at the southwest end of the mine [Fig. 9(c)]. Maximum depth measured within the scour pit was 13.27 m. A subtle ripple field trending north–northeast–south–southwest was again evident during this survey, although they appear smaller and less continuous than during the initial survey. Ripple heights were on the order of 10 cm and the wavelength was $\sim$50 cm. The mine sunk 6 cm since the previous survey three days earlier, resting at a depth of 12.86 m. Depth of the ambient seafloor was 13.15 m, resulting in an observed burial of 38.3%.

The survey of February 6 occurred 609 h after the mine was deployed. A ripple field was still visible at this time; however, it did not appear to be as well defined as it was in the previous survey [Fig. 9(d)]. The apparent wavelength of the ripples increased to $\sim$75 cm, while the ripple height appeared to remain constant. The scour pit at the southwest end of the mine continued to develop, with a maximum depth of 13.32 m. Depth of the mine was 12.84 m, 2 cm shallower than in the previous survey, however, well within the 5-cm vertical uncertainty of the sonar. Depth of the surrounding seafloor was measured at 13.11 m, resulting in a percent burial of 42.6%. The mine appeared to the south of its original position indicated by the black dashed outline in the center of the image. Data from the orientation sensors within the mine did not indicate that the mine rolled since the prior survey. The orientation sensors did not measure cumulative roll, however; so, if the mine made a full rotation, the sensor would not have recorded any change. The maximum offset between the mine's position 609 h after deployment and its position 207 h after deployment was $\sim$1.5 m; a complete roll of the mine would account for 1.4 m. Roll measurements within the mine were made every 15 min, so if the roll were rapid the sensors would not record it. A storm event moved through the area causing elevated waveheights on January 24, 2003. It is, therefore, possible that the mine made a rapid and complete rotation at this time. Although the multibeam system has a horizontal accuracy of ± 1 m, there were no other offsets observed for the other mines during the same survey, suggesting that the offset was likely a true southward displacement by some mechanism such as rolling and/or horizontal translation.

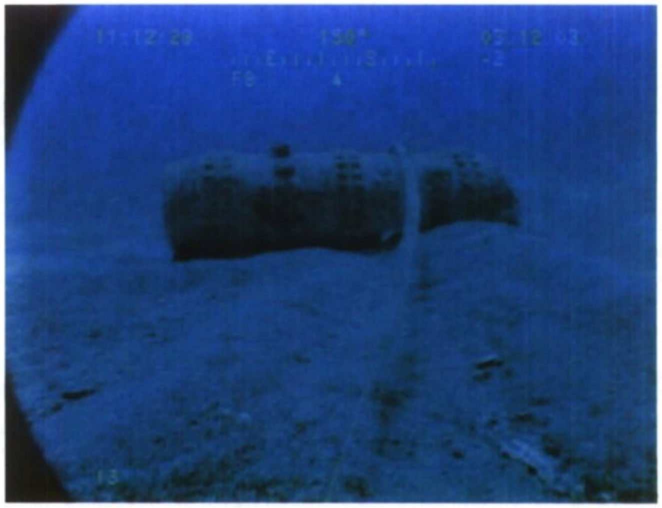

Fig. 10. ROV video still of the F8 mine taken on March 12, 2003, one day before the final survey over the mine. Camera is facing south–southeast showing a side view of the mine in the ripple field. The mine is approximately 1.50 m long.

The final survey over the F8 mine took place on March 13, 1451 h after deployment. Once again the mine appeared 1.6 m to the south of its original position [Fig. 9(e)]. This offset was within 10 cm of the offset observed during the February 6 survey, and strongly supports the idea that the mine made a complete roll during the experiment. The mine appeared nearly flush with the surrounding ripples. The ripples were very well defined, with a wavelength of $\sim$1.2 m and a height of 12 cm. The depth of the mine was 12.72 m with a surrounding seafloor depth of 13.00 m, resulting in an observed burial of 40.4%. The data seemed to suggest an anomalous shallowing of the mine and ambient seafloor depth by 12 cm. The combined vertical uncertainty of the multibeam system for both the February 6 and March 13 surveys can account for up to 10 cm of this discrepancy; the remaining 2 cm could be a result of a local change in the sound speed profile compared to the one being used by the multibeam system to calculate depth. The average sound speed during this survey was 1520.90 m/s; therefore, it would take an error of 14.02 m/s to account for the entire 12 cm, and only 2.3 m/s for the 2-cm change. It is also possible that an error existed at that time in the tide record used to correct the data during processing. Of these possibilities, we suspect that a small change in the local sound speed profiles was the most likely reason for error, because it is common to have occasional isolated small 2–3-m/s changes in sound speed in coastal settings. Regardless, percent mine burial by depth is concerned with the depth of the mine relative to the ambient seafloor and not the absolute depth of the mine or seafloor. Therefore, if the discrepancy in both seafloor depth and mine depth is the same, then the percent burial will not be affected. ROV video from March 13, 2003 showed that the F8 mine was only partially buried and surrounded by ripples at the end of

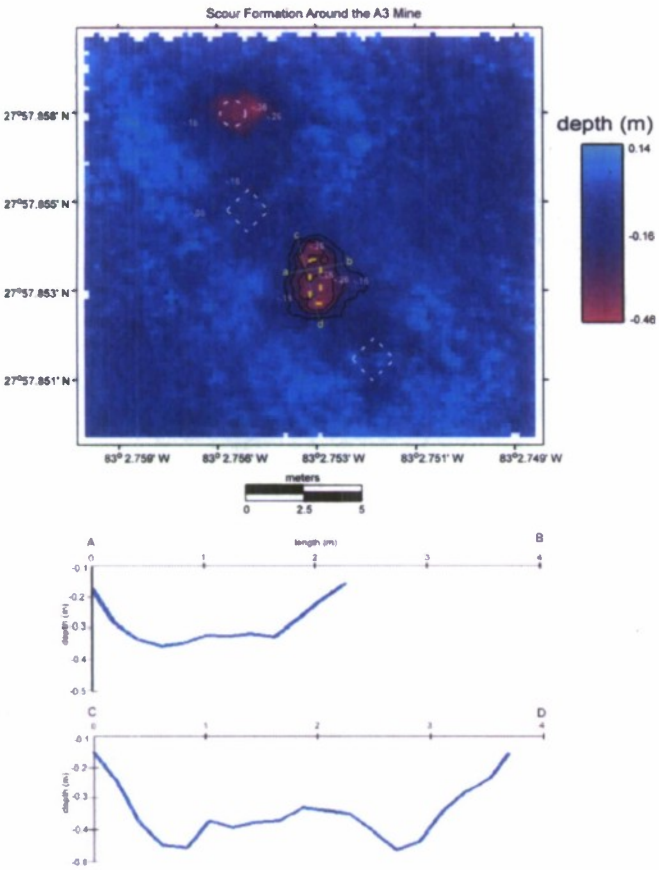

Fig. 11. Bathymetric finite difference grid between the first and final survey over the A3 mine. Contours are in 10-cm increments. Yellow outline denotes last position of mine as observed in the March 13 survey.

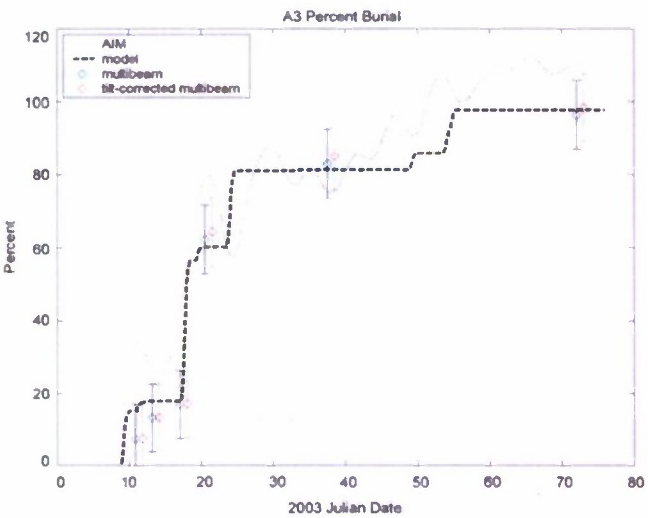

Fig. 12. Comparison of the mine (magenta), predicted (dashed), observed (blue), and tilt-corrected observed (red) percent burial for the A3 mine over the course of the experiment. Tilt-corrected values have been horizontally offset for clarity. Error bars represent the 5-cm uncertainty inherent in the multibeam system.

the experiment, thus corroborating what was determined by the relative depth difference between mine and seafloor observed in the multibeam data (Fig. 10).

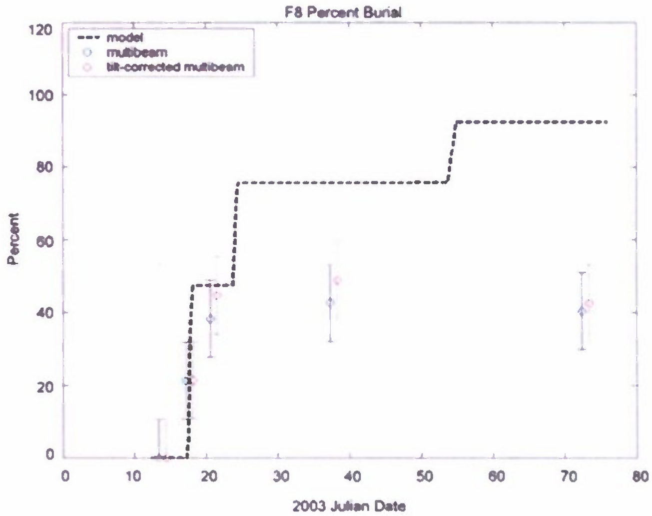

Fig. 13. Comparison of the mine (magenta), predicted (dashed), observed (blue), and tilt-corrected observed (red) percent burial for the F8 mine over the course of the experiment. Tilt-corrected values have been horizontally offset for clarity. Error bars represent the 5-cm uncertainty inherent in the multibeam system.

TABLE I

ALONG-TRACK BEAM SPACING FOR VARIOUS VESSEL SPEEDS. NUMBERS ARE IN METERS. ALL CALCULATIONS ARE BASED ON A PING RATE OF 10 Hz. AT VESSEL SPEEDS OF 5.5 kn OR GREATER, THE ALONG-TRACK BEAM SPACING BECOMES GREATER THAN THE BEAM FOOTPRINT IN 13 m OF WATER DEPTH [11]

vessel speed (kn)	along track beam spacing at 10 Hz (m)
2.5	0.13
3.5	0.18
4.5	0.23
5.5	0.28
6.5	0.33
7.5	0.38
8.5	0.43
9.5	0.48

B. Scour Analysis of the A3 Mine

Scour formation around and under mines is the driving mechanism for mine burial in noncohesive fine sand, and is the basis of mine burial probability models. To better understand scour formation during the experiment, scour formation around the A3 mine was analyzed. The presence of ripple fields in the coarse-sand site complicated the bathymetry and prevented scour analysis for mines deployed in that site. Wolfson [11] provides a complete discussion of the scour analysis performed on all the mines deployed in the two fine-sand sites.

Scour did not become evident around the A3 mine until the survey conducted 280 h after deployment (Fig. 7). Initial scour development was focused along the sides of the mine; however, the deepest scour occurred at the ends. Scour around the A3 mine was complicated by the presence of the two quadpods and

TABLE II
BEAM FOOTPRINT AND BEAM SPACING ALONG THE SEAFLOOR FOR VARIOUS DEPTHS AND BEAM POINTING ANGLES. BEAM POINTING ANGLE IS WITH RESPECT TO THE SONAR HEAD. TOP NUMBER IS THE BEAM FOOTPRINT (WIDTH) IN METERS, BOTTOM NUMBER IS THE BEAM SPACING IN METERS. THESE NUMBERS ASSUME A FLAT SEABED. WATER DEPTH IS DEPTH OF THE SEAFLOOR BELOW THE WATER SURFACE. CALCULATIONS ARE BASED ON THE FACT THAT THE SONAR WAS POLE-MOUNTED TO THE VESSEL DURING SURVEYS, AND THUS, IT WAS APPROXIMATELY 2 m BELOW THE ACTUAL WATER SURFACE [11]

water depth	Vertical (0°) 1.5° beamwidth 0.9° beam spacing	45° 2.1° beamwidth 1.3° beam spacing	60° 3.0° beamwidth 1.8° beam spacing
10 m	0.21 0.13	0.83 0.36	1.68 1.00
13 m	0.28 0.17	1.14 0.50	2.31 1.38
20 m	0.47 0.28	1.87 0.82	3.77 2.26

one spider deployed in the same area, which developed their own scour pits. The most pronounced scour was around the A3 mine, and it formed a pit with an approximate surface area of 8.60 m^2 and a total volume of 1.64 m^3 (Fig. 11). The pit was divided into three contour intervals, ranging in depth from -0.16 to -0.36 m. The long cross section (profile C-D) was approximately 3.75 m long with a maximum depth of 0.46 m. The short cross section (profile A-B) was roughly 2.4 m long and reached a depth of -0.35 m.

C. *Comparison With the VIMS 2-D Burial Model*

The VIMS 2-D burial model predicts percent burial of the mine given sediment size, bed stress, and mine diameter. NOAA WaveWatch3 monthly hindcast wave data are used to drive the model for wave-induced scour, by using linear wave theory to estimate near-bed wave orbital speed [3]. The percent burial can then be predicted by comparing the depth of the scour to the diameter of the mine. This allows for a direct comparison between predicted estimates of mine burial and direct observations from multibeam sonar data.

1) A3 Mine: The model was initialized with a local water depth of 12.81 m, obtained from the initial multibeam survey to pass over the area 49 h after divers positioned the mine. The model was then run from the time the mine was positioned, January 8, 2003, at 21:00:00Z, to the time of the last multibeam survey over the mine, March 13, 2003, at 02:00:00Z. Fig. 12 shows the direct comparison between the predicted percent burial using the VIMS 2-D burial model (dashed black line) and the observed percent burial obtained from the multibeam data (blue circles). The magenta line represents percent burial as measured by the mine itself, obtained by normalizing depth measurements from the internal pressure sensor by the initial value. Observed percent burial in the multibeam data is based off the shallowest point on the top surface of the mine, which can underestimate true burial of the mine due to pitch (tilting of the long axis of the cylinder). The predicted percent burial is based on the depth of the predicted scour in relation to the mine diameter, and therefore, it assumes a direct sinking of the mine with no concern for pitch. The degree of pitch (measured by sensors within the mine) can be used to calculate how much deeper the center point on the top surface of the mine is from the shallowest point observed in the multibeam images. The red circles depict this correction, which can be applied to the observed values for percent burial. Error bars on both blue and red circles represent the $\pm$5-cm vertical uncertainty of the multibeam sonar.

The comparison between the predicted percent burial from the model and the observed percent burial from the multibeam sonar shows a good agreement. In each instance, the predicted value falls within the possible range of multibeam values given the 5-cm vertical uncertainty of the sonar. This agreement holds even without the tilt correction. The rms error between the observed percent burial (blue circles) and the predicted percent burial is 3.8, indicating a strong correlation between the two.

2) F8 Mine: For the F8 mine, the model was initialized with a local water depth of 13.20 m, obtained from the initial multibeam survey to pass over the area 34 h after mine deployment. The model was then run from the time the mine was deployed, on January 11, 2003, at 23:00:00Z, to the time of the last multibeam survey over the mine, on March 13, 2003, at 10:00:00Z. Fig. 13 shows the direct comparison between the predicted percent burial using the VIMS 2-D burial model (dashed black line), the observed percent burial obtained from the multibeam data (blue circles), and the tilt-corrected values (red circles). The FWG mines only measured burial as a function of surface area rather than depth, so no comparison was made with data from the mine itself.

The comparison between the predicted percent burial from the model and the observed percent burial from the multibeam sonar does not show a good agreement. The trend throughout the experiment shows the modeled predictions are consistently higher than the actual observed values. Applying a tilt correction and taking the uncertainty of the multibeam into consideration is not enough to account for these discrepancies. The rms error for this comparison is 29.4, approximately an order of magnitude greater than the rms error for the A3 comparison.

TABLE III
DATA TABLE FOR THE A3 MINE. ALL NUMBERS ARE IN METERS EXCEPT WHERE NOTED

	0 h	49 h	103 h	197 h	280 h	688 h	1528 h
Depth of Mine	——	12.32	12.42	12.48	12.62	12.72	12.80
Cumulative Amount of Change	——	——	0.10	0.16	0.30	0.40	0.48
Average Depth of Seafloor	——	12.81	12.88	12.92	12.82	12.81	12.82
Cumulative Amount of Change	——	——	0.07	0.11	0.01	0.00	0.01
Scour Visible / Depth of Scour	——	no	no	no	yes 13.04	yes 13.18	yes 13.22
% Mine Burial from Multibeam (± 9.4% due to 5 cm uncertainty of sonar)	0	7.5	13.2	17.0	62.3	83.0	96.2
% Mine Burial from Model	0	14.9	17.8	17.8	60.1	81.2	97.7
Mine Heading (°)	-5.7	-6.9	-6.6	-6.6	-1.0	3.37	7.1
Mine Pitch (°)	-0.7	-0.3	-0.4	-0.4	-0.8	-0.9	0.6
Mine Roll (°)	-0.4	7.8	7.4	7.4	14.1	25.6	33.1

V. DISCUSSION

A. Assessment of Multibeam Imaging Capabilities Over the Mines

In some cases, the multibeam images depicted fairly accurate dimensions for the mines. In others, however, the mines did not image clearly at all. This is in contrast to the results from the Martha's Vineyard Coastal Observatory (MVCO, Edgartown, MA) experiment, where multibeam data not only showed correct dimensions of the mines but could also depict the tapered end of the FWG optical mines [12]. Multibeam surveys for the MVCO study were completed using a Reson 8125 sonar. The sonar operates at a frequency of 455 kHz with a subdecimeter resolution. Mayer *et al.* [12] state that distortion of the true mine diameter by the multibeam sonar may be due to the influence of neighboring cells on small targets during the gridding process. It is possible, therefore, that this is the case with the IRB data as well, and may explain some of distortion seen in the images, especially considering the lower 300-kHz frequency used at the IRB site.

The Kongsberg Simrad EM 3000 multibeam sonar has a maximum ping rate of 20 Hz in a very shallow water. Average vessel speeds during the IRB surveys ranged from ~2.5 to 9.5 kn. It is possible that, at a depth of ~13 m, the observed ping rate of 10 Hz (limited by the two-way travel time from the sonar to the furthest point imaged) is not sufficient to detect the mines at boat speeds of up to 9.5 kn. Indeed, the surveys that imaged the mines most clearly were conducted at vessel speeds of about 6 kn or less. Vessel speed affects the along-track distance between consecutive pings (Table I). At an average vessel speed of 9.5 kn and a ping rate of 10 Hz, there is an along-track distance of approximately 0.48 m between pings. For an FWG optical mine oriented parallel to the survey track, this would result in a maximum of three pings on the mine surface. In ~13 m of water depth, the beam footprint is ~28 cm (assuming a flat bottom). At vessel speeds of 5.5 kn and greater, the along-track

TABLE IV
DATA TABLE FOR THE F8 MINE. ALL NUMBERS ARE IN METERS EXCEPT WHERE NOTED

	0 h	34 h	125 h	207 h	609 h	1451 h
Depth of Mine	——	12.72	12.80	12.86	12.84	12.72
Cumulative Amount of Change	——	——	0.08	0.14	0.12	0.00
Average Depth of Seafloor	——	13.20	13.17	13.15	13.11	13.00
Cumulative Amount of Change	——	——	-0.03	-0.05	-0.09	-0.20
Scour Visible / Depth of Scour	——	no	no	yes 13.27	yes 13.32	yes 13.11
% Mine Burial from Multibeam (± 10.6% due to 5 cm uncertainty of sonar)	0	0	21.3	38.3	42.6	40.4
% Mine Burial from Model	0	0	0	47.4	75.5	92.5
Mine Pitch (°)	0	0	0	-2	-2	-1
Mine Roll (°)	-12	-11	-8	-1	0	0

beam spacing would be greater than the beam footprint, resulting in ground coverage that is not 100%. Furthermore, the EM 3000 beam spacing is controlled by fast Fourier transform (FFT) beamforming, causing the angular spacing of the beams to increase with distance from nadir. At nadir, the beam spacing is approximately 0.9°; however, this grows to 1.8° at 60° from nadir (Table II). As a result, target detection capabilities of the sonar degrade as the angle of incidence increases, which may help to explain the distortion of some of the images.

B. Comparison to the MVCO Experiment

The percent burial (defined as subsidence below ambient seafloor depth) results are in agreement to those seen at the MVCO mine burial site, where a similar experiment was run between 2003 and 2004 [13]. However, at the MVCO fine-sand sites, higher energy and a greater supply of muds resulted in scour pit infilling within two months, and complete burial and cover of the mines in seven months, whereas at IRB, the scour pits were not infilled. Sediment infilling of scour pits is quite important, as it can signify the difference between mines that can and cannot be readily detected by sidescan sonar. The mines deployed in the fine-sand sites off IRB became more visible in the sidescan imagery over time as a result of the growing scour pits around the mines, which served to form larger targets. In the case of the MVCO fine-sand sites, the mines became completely covered with sediment within seven months and no traces of them were evident in rotary sidescan images or multibeam sonar [13]. It should be noted, however, that while the MVCO experiment lasted seven months, the experiment off IRB only lasted two, but it appears that the greater percentage of mud, and to a lesser extent the higher energy, determines if infilling will occur and not the longer duration of the MVCO experiment.

VI. CONCLUSION

Over a two-month experiment, *in situ* mine burial and scour was observed using multibeam sonar bathymetry. This paper focuses on two specific mines: AIM (A3) deployed in the primary fine-sand site and an optical instrumented mine (F8) deployed in a coarser grained RSD. The A3 mine buried until the top of the mine was approximately flush with the ambient seafloor (96.2% burial). These results were typical for the remaining mines deployed in fine sands during the experiment [11]. The rate of burial for the A3 mine was greatest immediately following storm events, when increased wave energy resulted in

a greater amount of wave-induced burial. The same was not observed at the F8 mine. The F8 mine sank significantly less into the seabed, resulting in a much smaller percent burial (40.4%). The reason is believed to be due to the presence of wave orbital ripples that formed around the mine during the experiment.

The multibeam data from the IRB experiment were used to test the VIMS 2-D burial model. The results mirrored those seen in the comparison of the MVCO data with the model in [4] and [12]. In the case of mines located in fine sand, the model sufficiently predicts percent burial over the course of the experiment. In the case of mines deployed in coarse sand, however, the model greatly overpredicts the amount of burial. In coarse sands, it has been shown that the mines bury until they present approximately the same hydrodynamic roughness as the surrounding orbital ripples. The current model does not address bedform evolution and migration, which appears to be the cause of the model's poor performance in coarse sand. Another possible source of error between the observed data and the model involves how the model handles ambient seafloor depth. The model assumes that the local seafloor depth around the mine remains constant throughout the model run; however, multibeam data show localized erosion and deposition over the course of the experiment. Tables III and IV provide a concise summary of the multibeam observations and model predictions for the A3 and F8 mines, respectively.

Multibeam data from the IRB experiment were also used to perform analyses on the development on scour around mines. The presence of orbital ripples in the coarse-sand site complicated the bathymetry around the mines and resulted in a significantly lesser amount of scour. Therefore, scour analyses were not performed for mines deployed in this site. For mines deployed in the two fine-sand sites, the most pronounced scour occurred along the flat ends of the mines, regardless of mine orientation.

The results of this paper show that multibeam bathymetry data can be used in the detection of mines and observation of mine burial. Furthermore, these data show the VIMS 2-D burial model can sufficiently predict burial for cylindrical mines in fine sand, but that additional complexity is required to predict burial in coarser sediment.

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REFERENCES

[1] M. Richardson, P. Valent, K. Briggs, J. Bradley, and S. Griffin, "NRL mine burial experiments," in *Proc. 2nd Austr.-Amer. Joint Conf. Technol. Mine Countermeas.*, Sydney, Australia, 2001, CD-ROM.

[2] M. D. Richardson and K. B. Briggs, "Seabed-structure interactions in coastal sediments," in *Proc. 4th Int. Symp. Technol. Mine Problem*, Monterey, CA, 2000, CD-ROM.

[3] A. C. Trembanis, C. T. Friedrichs, M. D. Richardson, P. A. Traykovski, P. A. Howd, P. Elmore, and T. Wever, "Predicting seabed burial of cylinders by scour: Application to the sandy inner shelf off Florida and Massachusetts," *IEEE J. Ocean. Eng.*, vol. 32, no. 1, pp. 167–183, Jan. 2007.

[4] S. D. Locker, A. C. Hine, A. K. Wright, and D. S. Duncan, "Sedimentary framework of an inner continental shelf sand-ridge system, west-central Florida," *EOS Trans. AGU*, vol. 83, no. 47, p. F692, 2002.

[5] S. Griffin, J. Bradley, and M. D. Richardson, "Improved subsequent burial instrumented mines," *Sea Technol.*, vol. 44, no. 11, pp. 40–44, 2003.

[6] F. Pohner, "Processing of multibeam echosounder data," *Hydrographic J.*, vol. 50, 1990.

[7] J. H. Clarke, "Detecting small seabed targets using high-frequency multibeam sonar," *Sea Technol.*, vol. 39, no. 6, pp. 87–90, 1998.

[8] W. T. Collins and J. M. Preston, "Multibeam seabed classification," *Int. Ocean Syst.*, vol. 6, no. 4, pp. 12–15, 2002.

[9] W. T. Collins and J. L. Galloway, "Seabed classification with multibeam bathymetry," *Sea Technol.*, vol. 39, no. 9, pp. 45–49, 1998.

[10] J. V. Gardner, P. B. Butman, L. A. Mayer, and J. H. Clarke, "Mapping U.S. continental shelves," *Sea Technol.*, vol. 39, no. 9, pp. 10–17, 1998.

[11] M. L. Wolfson, "Multibeam observations of mine scour and burial near Clearwater, Florida, including a test of the VIMS 2D mine burial model," M.S. Thesis, College Marine Sci., Univ. South Florida, St. Petersburg, FL, 2005, unpublished.

[12] L. A. Mayer, R. Raymond, G. Glang, M. D. Richardson, P. Traykovski, and A. Trembanis, "High-resolution mapping of mines and ripples at the Martha's Vineyard Coastal Observatory," *IEEE J. Ocean. Eng.*, vol. 32, no. 1, pp. 133–149, Jan. 2007.

[13] P. Traykovski, M. D. Richardson, L. A. Mayer, and J. D. Irish, "Mine burial experiments at the Martha's Vineyard Coastal Observatory," *IEEE J. Ocean. Eng.*, vol. 32, no. 1, pp. 150–166, Jan. 2007.

[14] G. Gelfenbaum and K. Guy, "Bathymetry of west-central Florida," U.S. Geological Survey, St. Petersburg, FL, Open-File Rep. 99-417, 2000.

[15] D. F. Naar and B. T. Donahue, "High-resolution multibeam survey of ONR mine burial and scour study area near Clearwater, Florida," *EOS Trans. AGU*, vol. 83, no. 47, p. F692, 2002.

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